

Origin of Warm High-Velocity Dense Gas in ULIRGs

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Abstract

Possible origins of the molecular absorption discovered in some ULIRGs are investigated, based on a 3-D hydrodynamic model of star-forming interstellar gas in a galactic central region. The blue-shifted, warm ($\sim 200 - 300$ K), dense ($> 10^6 \text{ cm}^{-3}$) molecular gas suggested by CO absorption in IRAS 08752+3915 could be caused by the innermost region of the inhomogeneous inter-stellar medium (ISM) around a supermassive black hole. The infrequent observations of the dense gas with absorption in ULIRGs and Seyfert 2 galaxies could simply suggest that the high-density regions occupy only a very small volume fraction of the obscuring material. This is naturally expected if the inhomogeneous structure of the ISM is caused by non-linear development of instabilities. The model predicts a turbulent velocity field in the obscuring material, therefore blue- and red-shifted gases should be observable with nearly the same probability for the large enough statistical samples.

Key words: galaxies: Seyfert — galaxies: starburst — ISM: kinematics and dynamics

1. Introduction

Active Galactic Nuclei (AGNs) are believed to be highly obscured by dusty dense gas, and this contributes to huge radiative energy in some ultra-luminous infrared galax-

ies (ULIRG) (Imanishi & Dudley 2000). The central engines of type-2 Seyfert galaxies are also likely obscured by optically thick molecular gas, for which a torus-like geometry is often assumed. However, detailed structures of the ISM in deep centers of ULIRGs and Seyfert galaxies are still unclear. There are some indirect ways to infer their geometry and distribution using X-ray spectroscopy (e.g., Levenson, Weaver, & Heckman 2001), optical/infrared spectral energy distribution (SED) in comparison with model SED assuming the geometry of the torus (e.g., Pier & Krolik 1993; Elitzur 2006; Fritz, Franceschini, & Hatziminaoglou 2006), and optical/infrared absorption lines (e.g., Spoon et al. 2004; Imanishi et al. 2006; Imanishi et al. 2007; Levenson et al. 2007). Lutz et al. (2004) searched the $4.7 \mu\text{m}$ fundamental ro-vibrational band of CO in 31 bright local AGNs, but found no clear signature of absorption features, even in a Compton-thick Seyfert 2 nucleus, like NGC 1068. Recently, the *Spitzer* Infrared Spectrograph (IRS) revealed vibration-rotation absorption bands of gaseous C_2H_2 , HCN, and CO_2 as well as silicate absorption toward deeply obscured (U)LIRG nuclei (Spoon et al. 2004; Lahuis et al. 2007; Levenson et al. 2007). The absorption lines of C_2H_2 and HCN suggest the presence of warm ($T_g \simeq 200 - 700 \text{ K}$) and dense ($n_{\text{H}} > 3 \times 10^6 \text{ cm}^{-3}$) gas (Lahuis et al. 2007). They suggest that this gas occupies only a small fraction of the nuclear region ($\sim 0.01 \text{ pc}$) near the intrinsic mid-infrared source. The CO absorption features observed in ULIRGs are not resolved into individual lines, except IRAS 08572+3915, therefore the kinematics and structure of the absorbed material are still an open question.

Geballe et al. (2006) have found a broad CO absorption line toward IRAS 08572+3915 NW¹ using UKIRT/CGS4. The observations revealed the following features: 1) There are several blue-shifted components with $-160 \pm 25 \text{ km s}^{-1}$ for the high J lines ($P(6), P(8), \dots$), and $-150 \pm 25 \text{ km s}^{-1}$ and $-50 \pm 25 \text{ km s}^{-1}$ and for the low J lines ($P(1), R(1)$ and $R(2)$). 2) The hydrogen column density is approximately $1.5 \times 10^{22} \text{ cm}^{-2}$. 3) Mean temperature of the warm blue-shifted component is about 200 K.

¹ Optical classification of this galaxy is LINER (Veilleux et al. 1999). Imanishi & Dudley 2000, based on infrared spectroscopy, claimed that the AGNs of this galaxy and many other non-Seyfert ULIRGs are deeply buried in dusty gas.

Shirahata et al. (2007) have also detected the CO absorption in IRAS 08572+3915 NW using Subaru/IRCS. Their results are consistent with those of Geballe et al. (2006), showing a blue-shifted component (-160 km s^{-1}) with the temperature 273 K and cold gas at 27 K at the systematic velocity, assuming LTE. They also claim that there is a red-shifted component ($+100 \text{ km s}^{-1}$) seen in high J ($J > 4$) lines, implying higher temperature gas ($\sim 700 \text{ K}$). Column density of the warm component is $3 \times 10^{22} \text{ cm}^{-2}$.

These observations suggest that the absorption features do not simply arise from a smooth rotating molecular torus, which has been often postulated to explain the type-1 and type-2 AGNs. However, it is hard to determine the geometry and internal structures of the ISM in the central region of the galaxy from this observational information alone. Theoretical models used for SED fitting are phenomenological without kinematical information, therefore we cannot compare them with the absorption line observations.

In this paper, we investigate how the observational features suggested by the CO absorption in IRAS-08572+3915 NW can be understood in the context of a three-dimensional hydrodynamic model of the ISM around a supermassive black hole (SMBH) with nuclear starbursts (Wada & Norman 2002) (hereafter WN02). This is currently a unique model of the obscuring material around a SMBH on a several tens pc scale, characterized by a highly inhomogeneous, multi-phase, and turbulent ISM with a globally stable, geometrically thick structure. Three-dimensional radiative transfer calculations for this model revealed that CO luminosity distribution is also highly non-uniform (Wada & Tomisaka 2005). Although this is not a confirmed theoretical model applicable to the obscuring matter in all types of AGNs, it is worth verifying whether the features observed in the CO absorption lines in the ULIRG can be explained by the full 3-D hydrodynamic models.

2. Model and Analysis

2.1. A Hydrodynamic Model of the ISM around a SMBH

In the WN02 model, mass, momentum, and energy conservation equations with the Poisson equation are numerically solved with energy feedback from supernovae in a fixed gravitational potential. A rotating gas disk in a time-independent spherical potential is solved by 3-D hydrodynamic code. The mass of the BH is $M_{\text{BH}} = 10^8 M_{\odot}$. We also assume a cooling function $\Lambda(T_g)$ ($5K < T_g < 10^8 K$) with solar metallicity, heating due to photoelectric heating, and energy feedback from SNe. We assume a uniform UV radiation field ten times larger than the local UV field.

The hydrodynamic part of the basic equations is solved by AUSM (Advection Upstream Splitting Method) (Liou & Steffen 1993). (See details in Wada (2001); Wada & Norman (2001)). We use $256^2 \times 128$ Cartesian grid points covering a $64^2 \times 32 \text{ pc}^3$ around the galactic center (i.e. the spatial resolution is 0.25 pc). The Poisson equation is solved using the fast Fourier transform and the convolution method. The initial condition is an axisymmetric and rotationally supported thin disk (the scale height is 2.5 pc) with a uniform radial density profile and a total gas mass of $M_g = 5 \times 10^7 M_{\odot}$. Random density and temperature fluctuations, which are less than 1 % of the unperturbed values, are added to the initial disk.

Supernova (SN) explosions are assumed to occur at random positions on the disk plane. The average SN rate is $\simeq 0.8 \text{ yr}^{-1}$. The energy of 10^{51} ergs is instantaneously injected into a single cell as thermal energy. Thus the three-dimensional evolution of blast waves driven by the SNe in an inhomogeneous and non-stationary medium with a global rotation is followed explicitly, taking into account the radiative cooling.

WN02 showed that a globally stable concave “torus”, in which the gas is highly turbulent and inhomogeneous, is formed (See also figure 6). Figure 1 is a phase-diagram of the ISM in the torus at a quasi-steady state. Three dominant phases present: Hot gases around $T_g \sim 10^7 \text{ K}$ caused by SNe, warm gases around $T_g \sim 10^4 \text{ K}$, and cold, dense gases at $T_g < 100 - 1000 \text{ K}$. In terms of the observed CO absorption in IRAS 08572+3915,

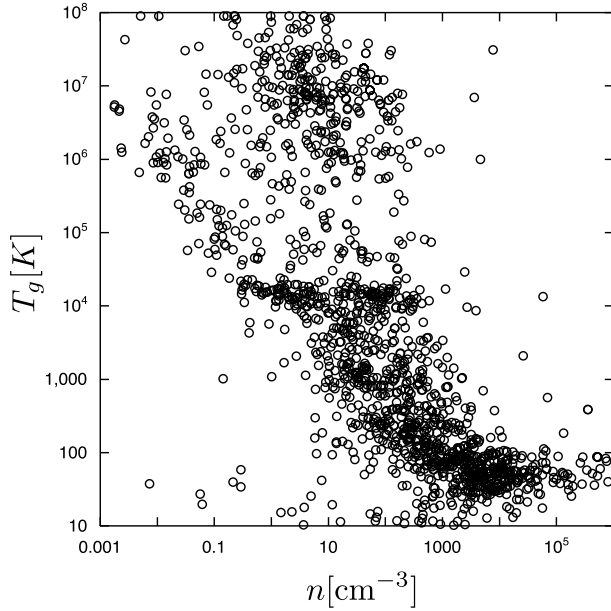


Fig. 1. Density-Temperature diagram of the ISM around a supermassive black hole with energy feedback from supernovae. The open circles represent 500 sampled point in the torus.

we are interested in kinematics and spatial location of the cold, dense media.

The size of the present torus model ($r \simeq 30$ pc) is much larger than the size (~ 2 pc) suggested by near- and mid-infrared high-resolution observations of type-2 Seyfert, e.g. NGC 1068 (Jaffe et al. 2004; Wittkowski et al. 2004). This difference actually reflects a fact that near/mid-infrared flux is originated from inner a few pc region of the dusty material around the AGN. In fact, a recent 3-D radiative transfer model assuming clumpy dust tori for NGC 1068 (Hönig et al. 2006) suggests that the outer radius of the torus that fits SED of NGC 1068 is 56 pc, while their H-, K-, and N-band images show their radii are 2.0-2.7 pc. In terms of ULIRGs, Levenson et al. (2007) suggested observed deep absorption features in mid-infrared indicate obscuration on scales of a few 100 pc. Probably the obscuring material in the central region of AGNs and ULIRGs is extended from a sub-pc to a sub-kpc scales with various physical/chemical conditions and structures.

2.2. Analysis of the Hydrodynamic Results

In order to find the blue- and red-shifted warm, dense gases suggested by the CO absorption line in the hydrodynamic model, we sample points with the following conditions from the 2000 randomly selected points in a half (i.e. $z \geq 0$) the “torus”.

1. Number density is $n \geq 10^6 \text{ cm}^{-3}$
2. Column density from the nuclear source to the observer $N \geq 10^{23} \text{ cm}^{-2}$
3. Temperature is $10 \leq T_g \leq 1000 \text{ K}$

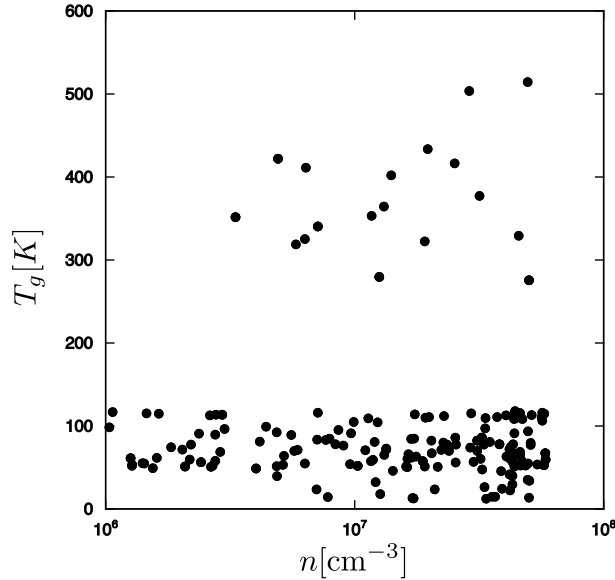


Fig. 2. Density and temperature of gases which are candidates for the absorbed gas.

Figure 2 shows number density and temperature of the selected points. It is clear that two components exist: cold gas with $T_g \lesssim 100 \text{ K}$ and warm gas with $300 \lesssim T_g \lesssim 500 \text{ K}$. Figure 3 shows the line-of-sight velocity of the selected points, V_{los} , as a function of their temperature. Most of the cold and warm components are distributed in the range of $|V_{\text{los}}| \lesssim 200 \text{ km s}^{-1}$. Spatial distribution of the selected points are shown in figures 4 and 5. The warm components are distributed around $2 \lesssim r \lesssim 4 \text{ pc}$ from the galactic center, and they are located just above the equatorial plane, i.e. $10 \lesssim |\theta| \lesssim 30^\circ$. Temperature of the warm component is higher for larger $|\theta|$, i.e. closer to the surface of the “torus”. The cold dense gases are located $2 \lesssim r \lesssim 10 \text{ pc}$ and near the disk plane ($|\theta| \lesssim 10^\circ$).

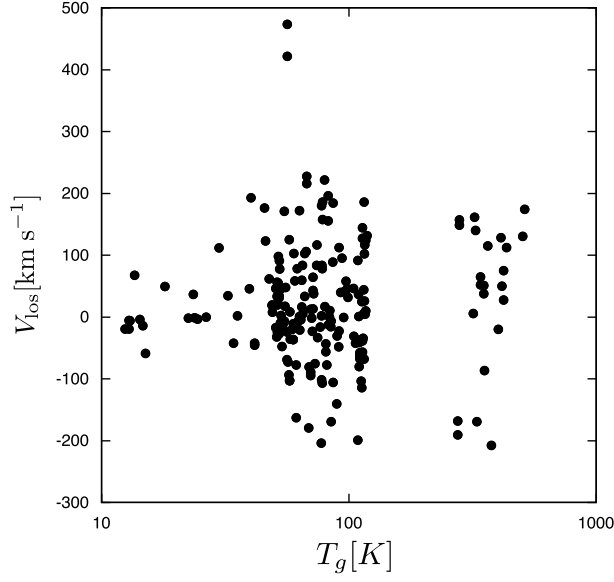


Fig. 3. Same as figure 2, but temperature vs. line-of-sight velocity.

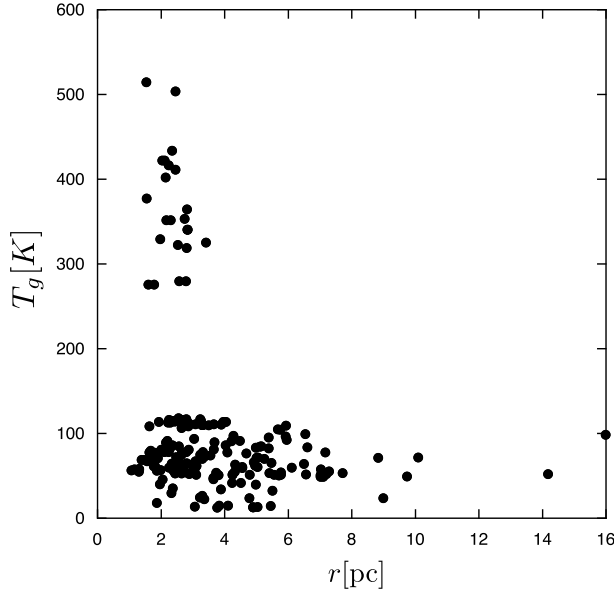


Fig. 4. Radial distribution of the selected points.

In summary, the absorbed material with $N > 10^{23} \text{ cm}^{-2}$, $n > 10^6 \text{ cm}^{-3}$, $|V_{\text{los}}| = 100 - 200 \text{ km s}^{-1}$, and $T_g \simeq 300 - 500 \text{ K}$ sits at the innermost region of the inhomogeneous torus as shown in figure 6 (the hatched regions). For the gas near the equatorial plane, the column density is too high to be observed as an absorption line for the continuum IR source. Therefore, if the ISM in the central region of ULIRGs, like IRAS 08572+3915,

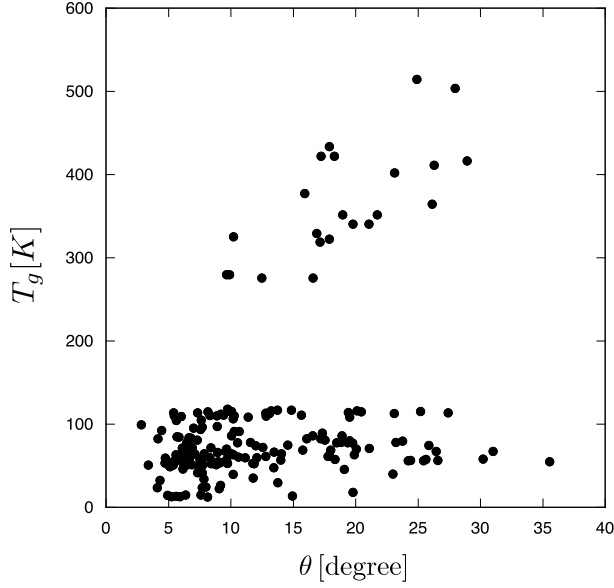


Fig. 5. Same as figure 4, but for temperature vs. position angle θ . $\theta = 0$ is on the equatorial plane of the torus.

is similar to the structure shown in figure 6, the viewing angle to observe the warm and dense gases as absorption is restricted. If this is the case, we can expect to observe high velocity, warm components as well as low velocity, cold components as absorption against the background continuum source, whose size is smaller than 1 pc. The high density gases in those regions have various velocity components, as shown in figure 3. Thus it is not necessary to observe only blue-shifted gas. In fact, Shirahata et al. (2007) also found a red-shifted gas component ($+100 \text{ km s}^{-1}$) in high- J transition, suggesting gas warmer than the blue-shifted component.

One should note that geometry of the “torus” in the present model depends on the supernovae rate, total gas mass, and the mass of a SMBH, since it is determined from a balance between energy input and dissipation rates under the effect of gravitational potential (WN02). Therefore, the absolute locations (i.e. r and θ) of the warm, dense gas around an AGN should depend on these parameters.

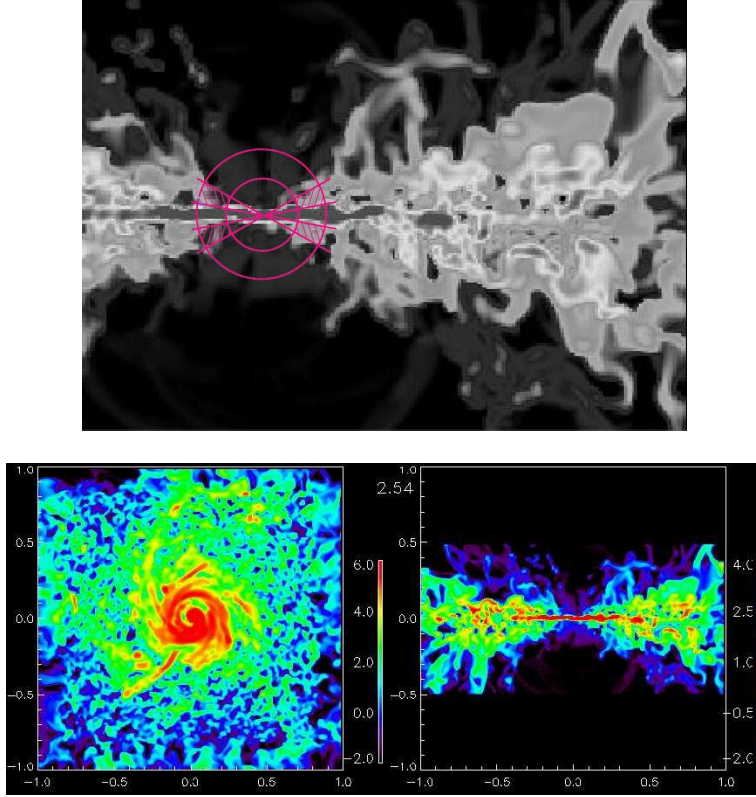


Fig. 6. (upper panel) Possible location (the hatched region) of the warm gas clumps suggested by CO absorption observations. See the lower panel, in which log-scaled gas density is shown at x-y and x-z planes (unit of density and scale are $M_{\odot}\text{pc}^{-3}$ and 32 pc).

3. Discussion

3.1. Volume-Filling Factor of the Warm, Dense Gas

In the present model of the torus, the high density ($> 10^6 \text{ cm}^{-3}$) gases have both red- and blue-shifted velocity for a line-of-sight. Since a volume fraction of these dense gases is expected to be very small (see discussion below), and the background continuum is emitted from a small region in the vicinity of the central engine, the chance to observe a dense blob with a particular velocity component by an absorption line should be very small. For example, as shown in figure 3, the blue-shifted component around -200 km s^{-1} exists in about 1/500 of the total volume of the torus whose radius is about 30 pc. Therefore, one possible explanation about the observed blue-shifted component is that the line-of-sight toward the AGN happens to graze the high-density clump which

is approaching us. If this is the case, since the motion in the torus is highly turbulent (WN02), we have nearly equal chance of observing red-shifted warm gas, too. The red-shifted warm gas found by Shirahata et al. (2007) may be explained by this picture, but observed samples are still too small to further compare with the model.

Recently Wada & Norman (2007) proposed a simple statistical theory of the structure of the inhomogeneous gas disk in galactic disks, which is caused by non-linear development of gravitational and thermal instabilities. Using three-dimensional hydrodynamic simulations, they show that the probability distribution function (PDF) of density $P(\rho)$ in a globally stable, inhomogeneous ISM is well represented by a single log-normal function over a wide density range, that is

$$P(\rho)d\rho = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{\ln(\rho/\rho_0)^2}{2\sigma^2}\right] d\ln\rho, \quad (1)$$

where ρ_0 is the characteristic density and σ is the dispersion. The simulations show that the dispersion of the log-normal PDF is larger for more massive systems. Using the PDF, it is straightforward to calculate a volume fraction of high density gas (f_c) above a given critical density (ρ_c):

$$f_c(\rho_c, \sigma) = \frac{1}{2} \left(1 - \text{Erf} \left[\frac{\ln(\rho_c/\rho_0) - \sigma^2}{\sqrt{2}\sigma} \right] \right). \quad (2)$$

The dispersion σ is then related to the average density, $\bar{\rho}$, i.e.

$$\sigma^2 = 2 \ln \left(\frac{\bar{\rho}}{\rho_0} \right). \quad (3)$$

It is also suggested that characteristic density ρ_0 is not very sensitive for changing the total gas mass. Suppose the column density toward the continuum source is 10^{22} cm^{-2} and the size of the ‘torus’ is 30 pc, the average density would be $\bar{\rho} \simeq 10^2 \text{ cm}^{-3}$. Therefore, using equation (3), we have $\sigma \simeq 3.0$ for $\rho_0 = 1 \text{ cm}^{-3}$. This leads to $f_c = 9.5 \times 10^{-4}$ and $f_c = 5.3 \times 10^{-5}$ for $\rho_c = 10^6 \text{ cm}^{-3}$ and 10^7 cm^{-3} , respectively. With this small volume-filling factor of the high-density gas in an obscuring material, it might be reasonable to expect there is a small chance of detecting a high-density clump with a particular velocity by absorption lines.

3.2. Difference between ULIRG and Seyfert1,2

Hao et al. (2007) observed 196 AGNs and ULIRGs using *Spitzer*/IRS, and found that quasars are characterized by silicate features in emission and Seyfert2s are dominated by weak silicate absorption, while ULIRGs are characterized by strong silicate absorption. Levenson et al. (2007) suggest that this difference in near-infrared spectra reflects a different geometry of the dusty material. They claim that clouds dominate the obscuration of Seyfert 1s and 2s, while on the other hand, central sources of ULIRGs are obscured mainly by smooth, geometrically and optically thick material with a steep temperature gradient. According to Lahuis et al. (2007), N_{H_2} for the nucleus of IRAS 08572+3915 estimated by infrared spectra obtained by *Spitzer* is $N_{\text{H}_2} \simeq 1.5 \times 10^{23} \text{ cm}^{-2}$. If the scale of the obscuring material is about 30 (100) pc, the average number density is $n \simeq 1.5 (0.5) \times 10^3 \text{ cm}^{-3}$. Using the log-normal density PDF in §3.1, we can estimate that the volume filling factor of those gases is about 20 (30) %, suggesting that the dusty gas that contributes to the silicate absorption is more smoothly distributed in the obscuring material than the warm, dense gas found by CO absorption.

Our result presented here is that at least the CO absorbed feature of IRAS 08572+3915 is not inconsistent with a model characterizing a dense clumpy medium around an AGN. Since the velocity field of the ISM is highly turbulent in the model, if individual high density clumps are not resolved, a broad absorption feature originating in dense gases with various velocity components can be expected in the obscuring material. If this is the case, the reason why CO absorption is not observed in Seyfert-2 (Lutz et al. 2004) can be understood by the low filling factor of the warm, dense gas in the obscuring material. As discussed in §3.1, if average gas density of the obscuring material around AGNs is smaller in Seyfert galaxies than in ULIRGs, a fraction of high-density clumps becomes small. This seems to be inconsistent with the result by Levenson et al. (2007), but probably dusty “clouds” in the obscuring material responsible for the near/mid-infrared SED are much more diffuse than those causing the CO absorption (see discussion above). The ISM around AGNs in ULIRGs and Seyfert galaxies are more or less inhomogeneous,

and if so its density PDF is expected to be approximately log-normal. Therefore, it is not surprising, if the “smooth” distribution of dusty gas that is preferable to the SED fitting would include higher-density clumps with a smaller volume-filling factor.

3.3. Limitations of the Current Model and Other Possibilities

In the present hydrodynamic model, heating due to the radiation from the AGN to dust is not taken into account. Temperatures of optically thick clouds at a distance of a few pc from an AGN with $L = 10^{12} L_{\odot}$ would be 300-1200 K (Elitzur 2006). Therefore the warm clouds near the surface of the clumpy “torus” might be warmer than 300 – 500 K, which is a result of the present model. Effects of X-rays are not included in the model either, which would be especially important for chemistry of molecules (Maloney et al. 1996; Meijerink et al. 2007). For highly inhomogeneous media like those seen in figure 6, hard X-rays could affect not only chemistry of the gas in the vicinity of the central source, but also the clouds inside the “torus”, because the column density and the ionization rate are not simply related to the distance from the central source (WN02). The effects of X-rays on the abundance and line intensities of CO and other molecules are investigated using the present hydrodynamic model and 3-D non-LTE radiative transfer calculations (Yamada, Wada, & Tomisaka, in preparation).

As an alternative interpretation of the blue-shifted warm gas could be originated in outflows from an accretion disk around a supermassive black hole. Using two-dimensional radiation-hydrodynamic simulations, Ohsuga (2006) found that an outflow is driven by radiation force due to a luminous accretion disk. However, the outflow velocity is extremely large ($\sim 0.1c$), and its temperature is $\sim 10^7$ K, therefore the outflow from the accretion disk itself does not explain the warm, blue-shifted gases discussed here. It might be possible however that, the hot outflow gas propagates outward, and it then cools and forms warm, dense cloudlets by the thermal instability at a few pc from the accretion disk. Unfortunately long-term evolution of the outflow from the accretion disk and its interaction with the ISM on several tens pc scale is still an open question.

4. Conclusion

Based on the analysis presented here, we could conclude that the blue-shifted, warm, dense molecular gas in IRAS 08752+3915 NW suggested by recent high-resolution observations by Subaru/IRCS can be caused by high-density clumps in the inhomogeneous inter stellar matter around a supermassive black hole. The small possibility of observing the CO absorption in ULIRGs and Seyfert 2 galaxies could be simply interpreted as indicating that the high density regions occupy a very small volume fraction ($< 10^{-3} - 10^{-4}$) in the obscuring material with a turbulent velocity field. This is naturally expected if the inhomogeneous material is caused by non-linear development of instabilities and random processes (e.g. stochastic explosions of supernovae and interaction with inhomogeneous ISM) in a globally quasi-stable system.

However, this model is still a presumption until the absorbed features in near infrared spectra of many ULIRGs and Seyfert 2 galaxies are resolved and details of the kinematics of the obscuring material are clarified by future observations. It is also necessary to improve numerical models of the ISM in the central region of active galaxies by taking into account more realistic treatment of chemical reactions of molecular gas and radiative transfer in terms of AGNs and star forming regions.

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